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An Experimental Microwave Heating System for a 120-mm Munition

by Robert Tan, Tim Vong, and Stephen Howard

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An Experimental Microwave Heating System for a 120-mm Munition

Robert Tan, Tim Vong, and Stephen Howard
Sensors and Electron Devices Directorate

Abstract

This report details an experimental microwave heating system designed for use with a 120-mm munition. The system operates at 2.45 GHz, using slotted waveguide radiators. The reported temperature measurements show relatively uniform heating of a surrogate 120-mm munition. Experiments at the Army Research Laboratory have shown that a munition's propellant heated for a few minutes by microwaves to 49°C has characteristics similar to those of propellant that has been temperature-conditioned to 49°C for several hours. In particular, this heating increases the munition's muzzle velocity about 5 percent, thus enhancing its performance.

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Introduction

This report describes the design and testing of a microwave system for heating a 120-mm munition. It is well known that the performance of direct-fire kinetic-energy ammunition improves with increased preignition temperature. At 49°C, muzzle velocity increases approximately 5 percent above that of a munition at an ambient temperature of 25°C. Previous experiments at the Army Research Laboratory (ARL), based on earlier in-situ microwave propellant heating concepts and techniques originated by Scannell [1], have shown that propellant heated to 49°C by microwaves over a few minutes has ignition characteristics similar to those of propellant that has been temperature-conditioned for several hours to 49°C [2]. These initial experiments used a crude microwave system that did not uniformly distribute the microwave energy and, therefore, did not uniformly heat the propellant [3]. Thus, a microwave system was developed that could do this. Uniform heating is essential if very rapid heating is desired; otherwise, the heating is limited by the thermal conduction time.

This new system is designed to (1) accept a typical 120-mm munition and (2) heat the munition more uniformly to 49°C within 10 s, given enough microwave power. The time required to raise the propellant temperature a given amount is essentially a linear function of the microwave power given by

$$\Delta t(s) = \frac{m(\text{kg})c_p(\text{J/kgK})\Delta T(\text{K})}{P(\text{W})} , \quad (1)$$

where P is the power, m is the mass, c_p is the specific heat, ΔT is the rise in temperature and Δt is the time to raise the temperature. For the 120-mm munition, we estimated that it contains 7.9 kg of propellant that has a specific heat of 1340 J/kgK. Therefore, it takes 26 kW to raise the propellant 25°C in 10 s assuming all the microwave power is absorbed by the propellant. However, measurements of the shell casing have shown that 74 percent of the microwave power is transmitted to the propellant, 23 percent is reflected, and the remaining 4 percent is absorbed by the casing. Thus, about 33 kW would be needed to raise the temperature by 25°C in 10 s. This power can currently be generated with off-the-shelf commercial magnetrons. These calculations assume that the temperature of all the propellant is increased 25°. Computer simulations and laboratory measurements suggest that only the propellant in the outer portion of the munition needs to be heated to obtain the same ballistic improvement as obtained by heating the entire propellant load. If this proves to be true, less power will be required.

Design

The 120-mm munition has a diameter of 15.5 cm. The length of the area with propellant to be heated is about 46 cm, as shown in figure 1. The heating system is designed to uniformly heat the propellant through the casing of the 120-mm munition. The casing is made of a nitrate-impregnated cardboard coated with a thin antistatic layer containing aluminum.

The heating system consists of six identical waveguide sections that have four radiating slots. Each section is fed at the base as shown in figures 2 and 3. The result is a total of 24 radiating slots, which are used to distribute the microwave energy over the surface of the munition. The six slots in the feed are numbered 1 through 6, starting with slot number 1 at the input of the feed. For convenience, the slots in the six sections are numbered from 1 to 24, with slots 1 through 4 on section 1 (fed by the base slot 1), with slot 1 being the slot one-quarter wavelength ($\lambda/4$) from the shorted end, and slots 5 through 8 on section 2, and so on. The system is constructed using standard WR-284 waveguide and is designed to operate at 2.45 GHz. This frequency was chosen because the propellant is quite lossy at 2.45 GHz and because inexpensive magnetrons, such as those used in commercial microwave ovens, produce this frequency and are readily available.

Figure 1. Cross section of 120-mm munition.

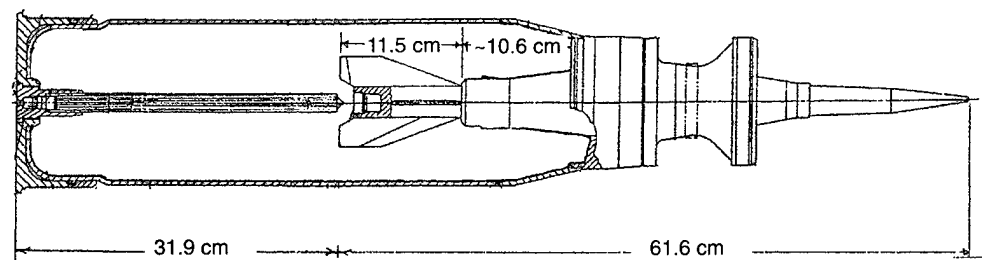


Figure 2. Waveguide section (with radiator slots and tuning screws) alongside base feed.

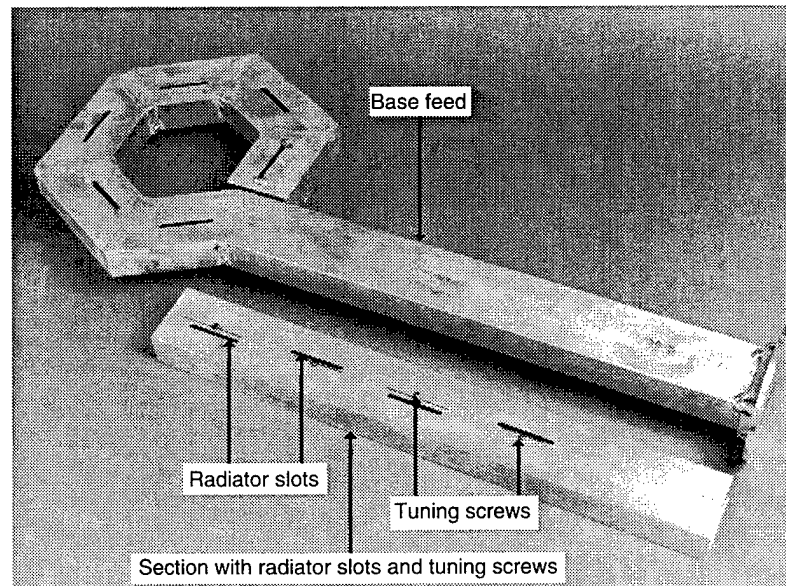
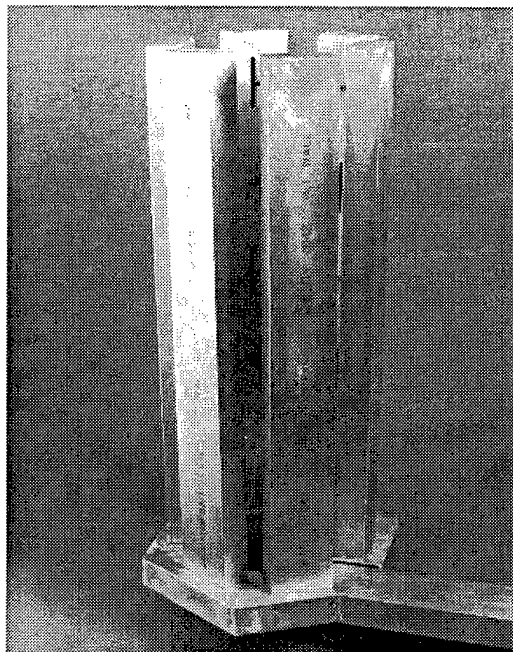


Figure 3. 2.45-GHz microwave heating system.



Slot Placement

Figure 4 shows the dimensions of the six identical waveguide sections, each of which is fed by a slot in the base. Each waveguide section has four slots arranged on either side of the centerline on its broad interior wall. All the slots are a half free space wavelength ($\lambda/2 = 15.16$ cm) long and are placed one-half the waveguide wavelength ($\lambda_g/2 = 29.41$ cm) apart. Waveguide wavelength is given by

$$\lambda_g = \lambda \left[\epsilon_r - \left(\lambda / \lambda_c \right)^2 \right]^{-0.5}, \quad (2)$$

where the waveguide cutoff wavelength, λ_c , is twice the broad dimension (a), or $\lambda_c = 2a$, and ϵ_r is the relative permittivity of the material filling the guide. In this case, the guide is filled with air ($\epsilon_r = 1$) and $a = 7.21$ cm. The last slot is placed $\lambda_g/4$ from the end of the guide, which is short circuited. The slots in the feed are also $\lambda/2$ long and separated as close to $\lambda_g/2$ as possible, given the mechanical restraints of forming a circular structure to place the radiating elements relatively equally around the 120-mm munition. The dimensions are shown in the mechanical drawings in the appendix. The current distribution in a short-circuited guide is shown in figure 5. The current pattern repeats itself every $\lambda_g/2$, with only the current direction changing every $\lambda_g/2$. For a slot to radiate, it must cut the path of the current, which is why the slots are offset from the center. The larger the offset from the center, the more power is radiated because more current is flowing across the slot at the edges of the guide. The slots are placed on alternate sides of the centerline so that the current flows in the same direction across each slot. This provides a same-phase field radiating from each slot, preventing nulls in the field due to phase cancellations, which would not uniformly heat the munition. To determine the exact location of each

Figure 4. Position and dimensions of six slotted waveguide sections.

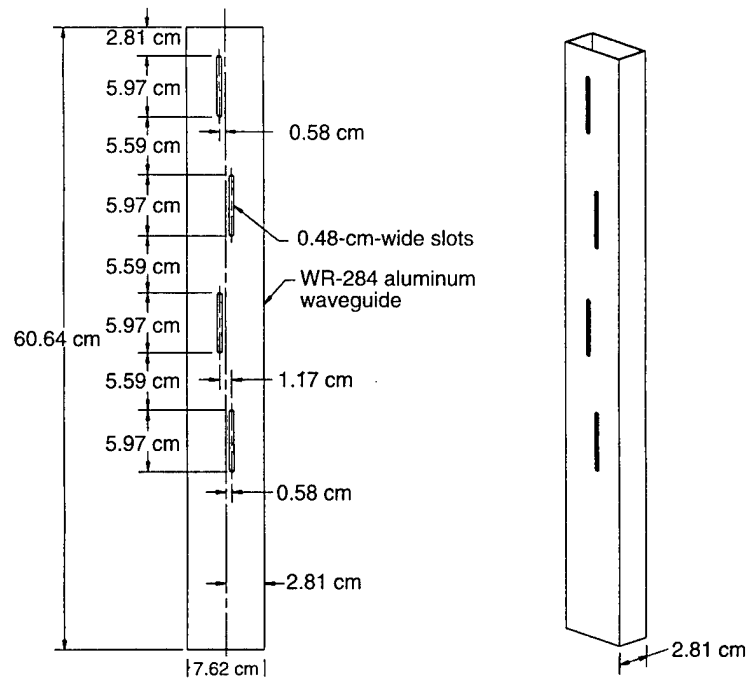
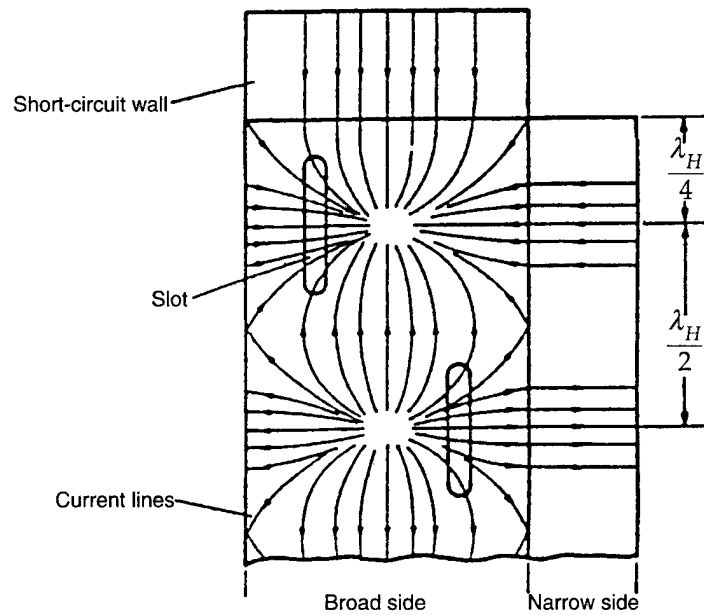


Figure 5. Current distribution in shorted waveguide section.



slot from the centerline, each slot is represented as a shunt impedance. If the slot is $\lambda_g/2$ long, the reactance becomes zero and each slot can be modeled by real shunt resistance (R). The normalized conductivity Z_L/R is given by

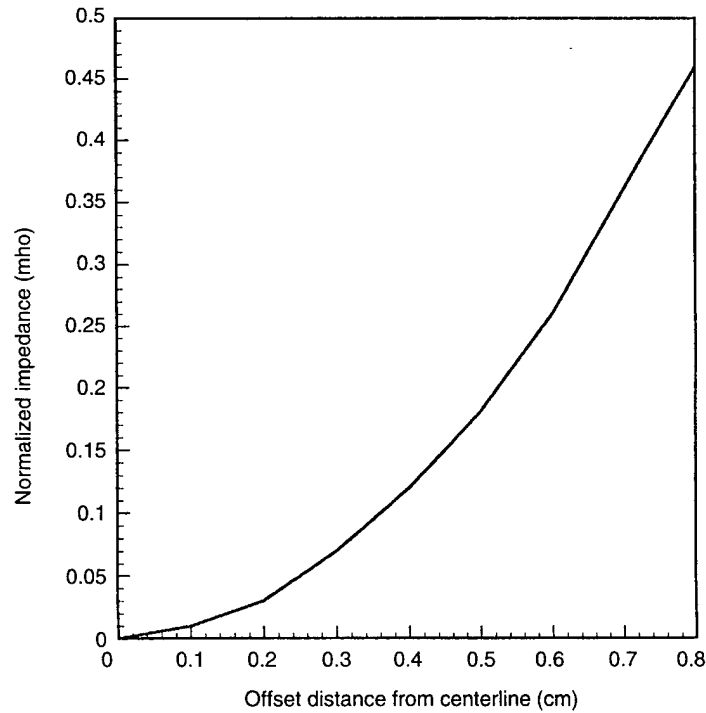
$$\frac{Z_L}{R} = \frac{480}{73\pi} \frac{a}{b} \frac{\lambda_g}{\lambda} \cos^2\left(\frac{\pi\lambda}{2\lambda_g}\right) \sin^2\left(\frac{\pi x_1}{a}\right), \quad (3)$$

where Z_L is the characteristic impedance of the guide, λ_g is the waveguide wavelength, λ is the free-space wavelength, $a \times b$ is the interior cross-section dimensions of the waveguide, and x_1 is the offset distance from the centerline of the slot [4]. To match the multiple slots with minimum reflection, the resulting shunt resistance of the slots must equal the characteristic impedance of the guide or, for four slots,

$$Z_L = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}. \quad (4)$$

If all slots are positioned the same, all values of R are equal and $Z_L/R = 1/N$ where N is the number of slots. Therefore, in our case with four slots per waveguide section, $Z_L/R = 1/4$. In figure 6, x_1 is plotted as a function of Z_L/R , given $\lambda = 12.24$ cm, $\lambda_g = 23.1$ cm, $a = 7.2$ cm, and $b = 3.4$ cm. From figure 6, $x_1 = 0.59$ cm for $Z_L/R = 1/4$. The feed section has 6 slots, so $Z_L/R = 1/6$ and, again from figure 6, $x_1 = 0.5$ cm.

Figure 6. Offset distance from centerline (x_1) as function of normalized impedance.



Slot Tuning

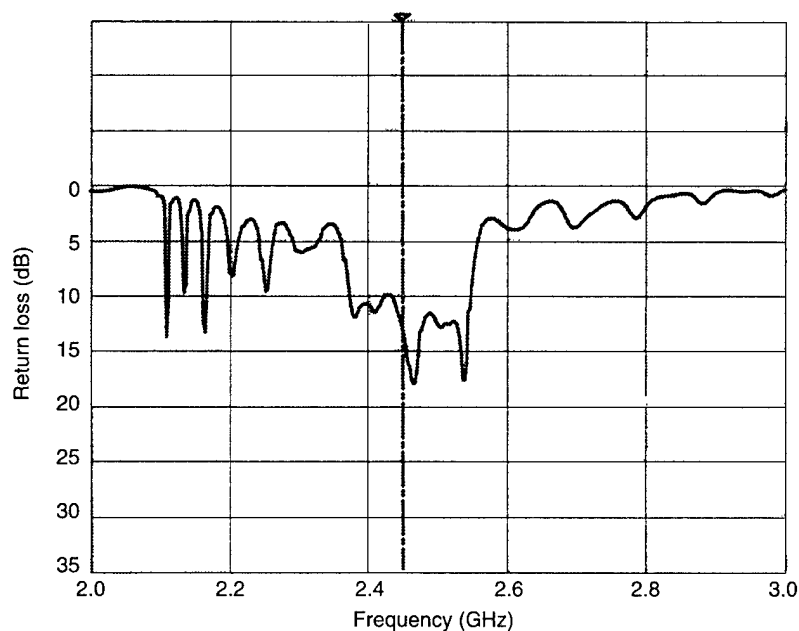
Moving the position of a section slot is not the only way to adjust the power radiated; it can also be adjusted by placing a tuning screw next to the slot, as shown in figure 3. Changing the length of the screw effectively moves the position of the slot [4].

Fabrication and Measurements

Initially a single test section was fabricated with four slots. The measured return loss is plotted in figure 7 and shows a return loss of 14 dB at 2.45 GHz. With these favorable results, the complete heating system could be fabricated with no modifications to the calculated dimensions. The heating system was fabricated from standard aluminum WR-284 waveguide. (See the appendix for mechanical drawings.) Unfortunately, every other slot in each of the six sections was fabricated with $x_1 = 0.47$ cm instead of 0.59 cm waveguide; to compensate, tuning screws were added toward the center of the guide adjacent to each slot, as shown in figure 3. The return loss measurement of the heating system is 15 dB at 2.45 GHz, as shown in figure 8. The transmission from each slot was measured by placing a waveguide-to-coaxial transition over each slot and measuring the transmission loss using a network analyzer. Ideally, the transmission measurement should be -13.8 dB if each slot radiated $1/24$ of the input power. The actual measurements of the system with no tuning are shown in table 1.

The standard deviation is 0.98 dB with a maximum difference of 3 dB between the slot radiating the most power and the slot radiating the least power. With tuning screws, the power transmitted from each radiator slot was adjusted for more even distribution of power. Table 1 also shows the transmission measurement after tuning the system.

Figure 7.
Measured
return loss for
test section
with four slots.



After tuning, the standard deviation is reduced to 0.83 dB, with a maximum difference of 3 dB of transmitted power between the slot radiating the most power and the slot radiating the least power.

Figure 8. Measured return loss for complete system.

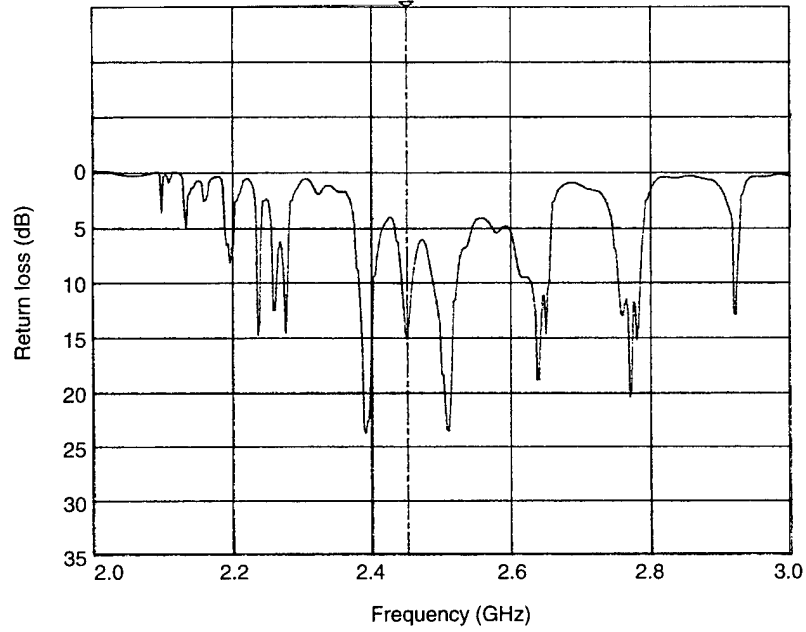


Table 1. Microwave transmission (by slot) before and after tuning, and temperature after 2 min heating.

Slot no.	S_{21} (dB)		Temperature after 2 min heating ($^{\circ}\text{C}$)
	Before tuning	After tuning	
1	-15	-14	33
2	-15	-15	37
3	-16	-15	38
4	-15	-15	38
5	-14	-14	38
6	-16	-14	37
7	-14	-13	39
8	-16	-14	37
9	-16	-16	35
10	-17	-16	36
11	-15	-15	36
12	-15	-15	36
13	-16	-13	32
14	-15	-14	33
15	-14	-14	34
16	-15	-14	35
17	-16	-14	32
18	-17	-15	33
19	-17	-15	34
20	-16	-15	34
21	-16	-15	32
22	-17	-14	33
23	-14	-13	35
24	-15	-15	36

Heating Measurements

For safety reasons, a live 120-mm munition could not be used in these initial heating experiments. Instead a 15-cm-diameter, 46-cm-long acrylic tube was filled with a surrogate that had a permittivity similar to the actual propellant [3]. The relative permittivity of graphitized and nongraphitized JA2 propellant is $3.5 - j0.65$ and $4.1 - j0.75$, respectively.

The surrogate used for the experiments is a mixture of sand, 1 percent table salt, and 3.75 percent water by weight, which had a measured permittivity of $3.8 - j0.76$. To quickly assess the uniformity of the heating, we used the sand mixture in conjunction with thermal paper to generate a picture of the temperature variations in the sand. The thermal paper was formed into a cylinder and placed around the inner diameter of the acrylic tube and also was cut into 15-cm-diameter circles, which were layered axially in the sand. The thermal paper begins to show darkening at 70°C ; therefore, the sand needed to be heated to at least this temperature. Because of the available source power, about 10 min elapsed before the thermal paper showed any darkening. The images made with the thermal paper were qualitative and were used in making adjustments to the radiator tuning screws. Unfortunately, the images did not photocopy well enough for publication in this report. A thermistor was also used to take temperature measurements in the sand. Twenty-four positions were measured 2.5 cm radially into the sand in front of the 24 section slots. Table 1 also shows the temperature in degrees Celsius after 2 min of heating. The standard deviation is 2°C .

Conclusions

A microwave heating system was designed and tested to heat the propellant in a 120-mm munition. A mixture of sand, salt, and water that has roughly the same permittivity as the propellant was used in the heating experiments. Both thermal paper and thermistors were used to measure the temperature throughout the propellant. The thermal paper was only used to give a qualitative picture of the uniformity of the heating and to assist in making adjustments to the system. The thermistor measurements were made in 24 positions spaced evenly throughout the propellant. After 2 min of heating, the standard deviation of the measured temperature was 2°C . This deviation can probably be improved by correcting the 20-percent error made in positioning half the section slots. The tuning screws helped to correct the error but could not completely compensate for the error in slot placement. Based on the mass of the propellant, its specific heat, and the efficiency of the microwave system, 26 kW of microwave power are needed to raise the temperature of the propellant in a 120-mm munition by 25°C in 10 s.

Work is being done that suggests that only a fraction of the propellant needs to be heated to obtain essentially the same ballistic improvement as heating all the propellant. If this is true, the microwave energy required is reduced in proportion to the mass of the propellant to be heated.

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A-4. Leaky waveguide assembly drawing	16

Figure A-1. Microwave input feed for leaky waveguide system.

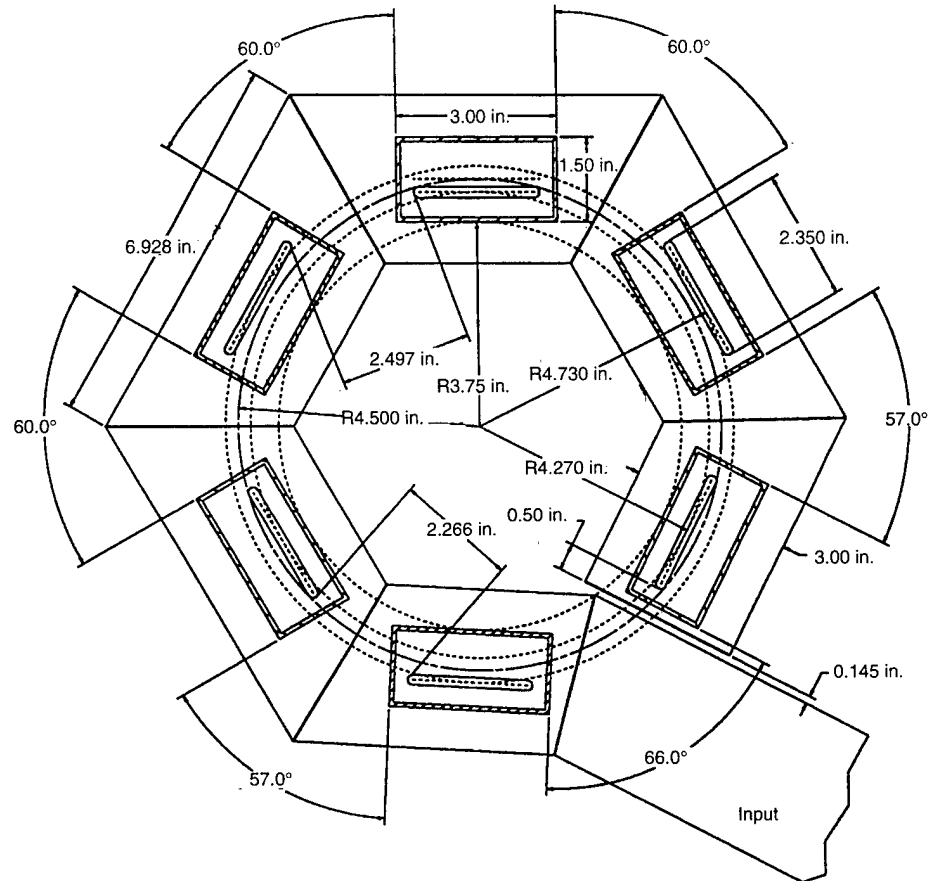


Figure A-2. Waveguide input feed for leaky waveguide system.

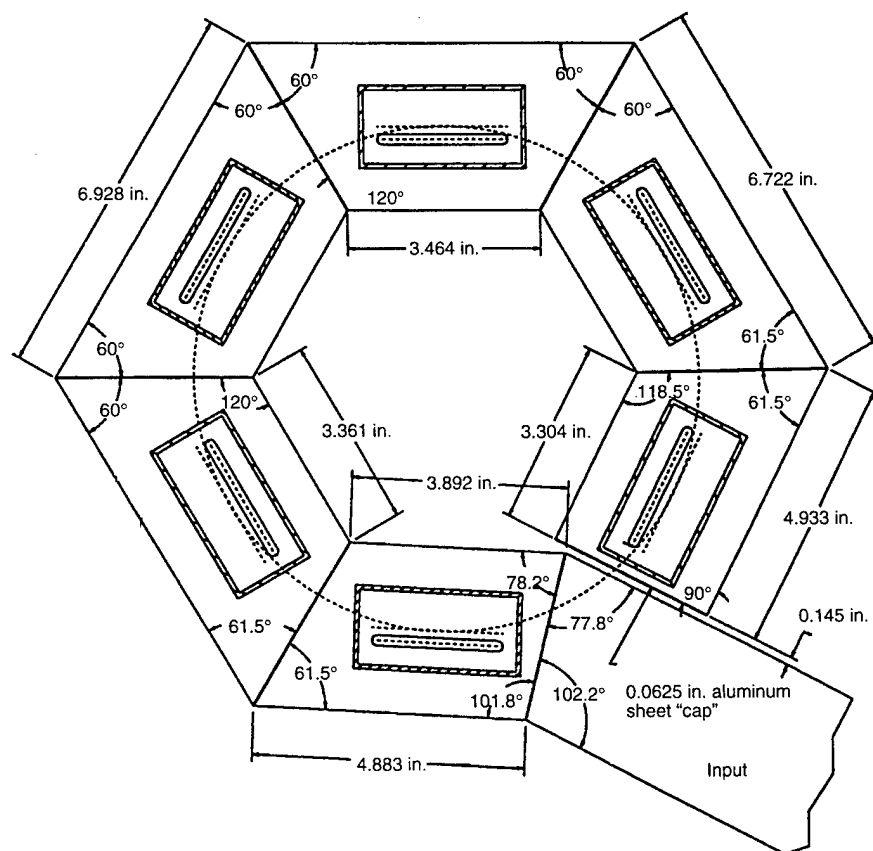


Figure A-3. Waveguide input feed for leaky waveguide system showing position of slotted waveguide radiators.

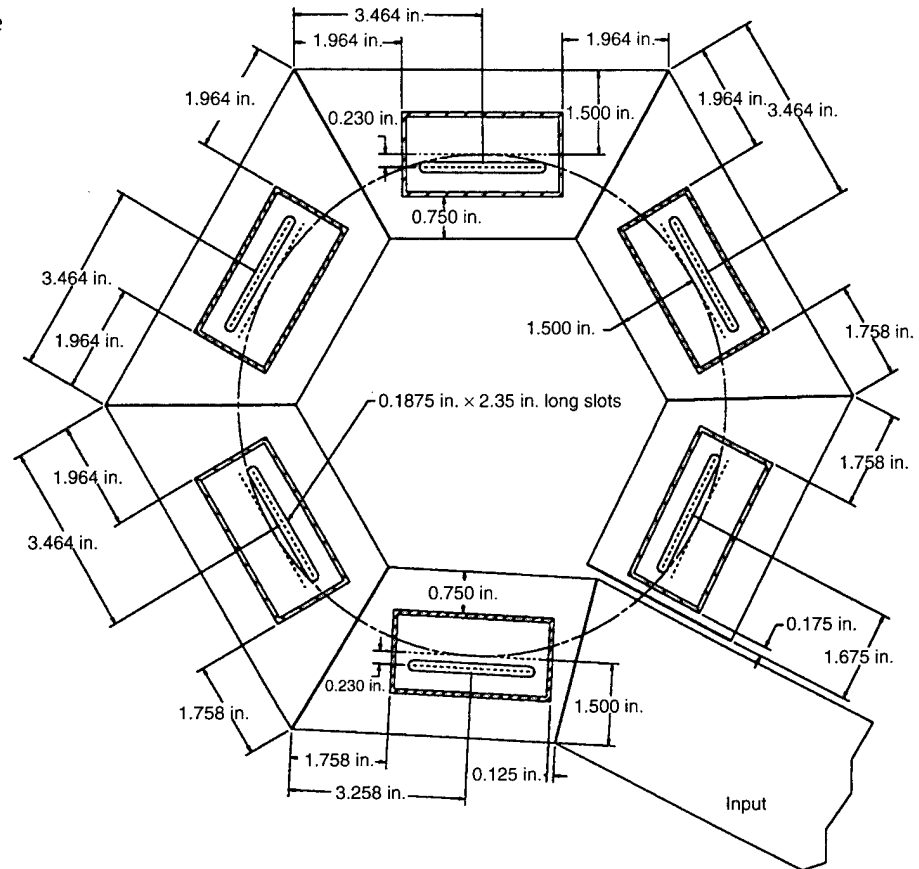
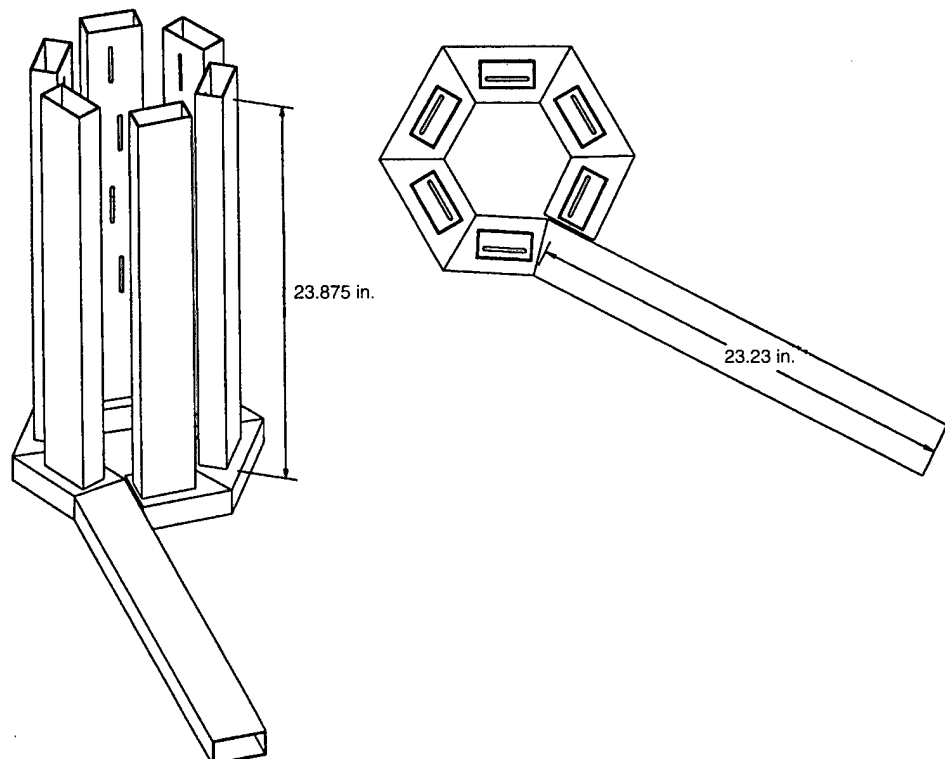


Figure A-4. Leaky waveguide assembly drawing.



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